4.1 X-ray Optics Fabrication and Metrology

The APS users have availed themselves extensively of our capabilities in the areas of metrology, thin film deposition, and crystal fabrication over the past year. A new interferometer for more direct monitoring of a polished surface during the polishing process and an ellipsometer with an *in situ* capability for the large deposition system have been added to enhance these capabilities with a particular emphasis on achieving smoother surfaces and thinner films. Furthermore, a specialized polisher is being commissioned to further enhance the polishing capabilities available to users, and an atomic force microscope is also being commissioned to enhance the metrology capabilities. Finally, an x-ray reflectometer using a standard tube source for rapid monitoring of multilayer x-ray performance and of layer thicknesses, in order to provide very rapid feedback for deposition parameters, is being commissioned. This instrument will enhance the ability to rapidly achieve a desired multilayer reflecting energy at a given angle of incidence. Progress in side-cooled mirror design for mirror optics (needed with future increases in storage ring current) is also discussed in this section.

4.1.1 X-ray Optics Metrology Laboratory

Thanks to fruitful collaborations between the synchrotron radiation community and mirror manufacturers, most of the major mirror vendors have developed their own metrology facilities for evaluation during the fabrication process and for their quality control. However, considering the high cost of a single synchrotron radiation mirror combined with the required delivery time, it is wise, before final acceptance, to independently check the purchased mirror and see if it meets the prescribed specifications. The metrology facility at the APS is designed to help the users fulfill this need. It is equipped with four major instruments, housed in an environmentally controlled Class 100,000 clean room. These instruments include a long trace profilers (LTP), a WYKO-6000 figure interferometer, a WYKO TOPO2D/3D roughness profiler, and an atomic force microscope (AFM)—a TOPOMOTRIX Explorer system. The three first instruments are noncontacting interferometers; the AFM can function in either a contact or a noncontact mode. The LTP is housed in a Class 100 clean enclosure in which the temperature fluctuation is controlled to within $\pm$ 0.1°C, in order to minimize system errors. These instruments cover a wide range of spatial frequency and allow one to determine the power spectral density function (PSD). The PSD gives the height distribution of the mirror surface as a function of spatial frequency, which permits one to predict the x-ray performance of the mirror more precisely than considering just figure and finish. Finally, a visible light microscope is also available for visual inspection of optical surfaces.

Some Selected Results

During the last fiscal year, over 15 major beamline mirrors, as well as several bending mechanisms and numerous small optical substrates, have been characterized at the metrology laboratory of the APS. The mirrors came in a variety of shapes (flat, cylindrical, spherical, and elliptical), with lengths up 1.2 m. Typical mirror substrate

materials are ULE, Zerodur, and single silicon crystals, with slope errors 5 µrad root mean square (rms), and microroughness 3 Å rms. Major manufacturers include Bœing, Zeiss (Germany), Seso (France), and Beam Line Technologies.

Most mirrors are for the APS users from BESSRC, Bio, IMCA, and UNI CATs. In addition, the needs of other synchrotron radiation facility users was also supported, including CHESS (one multilayer mirror) and the Advanced Light Source (two LTP spherical reference mirrors).

Also, in addition to intergroup collaborations involving efforts in metrology-fabrication-deposition, the metrology lab has seen an increase in requests for applications other than for synchrotron radiation, mainly from other divisions at ANL. The work includes evaluation of surfaces, such as diamond-like-coated SiC seals (Chemistry Division) and substrates for a mm-wave cavity project (ASD-APS).

Comparison between LTP and X-ray Profiles

Recently, a comparison made between LTP measurements and those obtained using x-ray diffraction showed the usefulness of the LTP as a rapid and accurate means of evaluating synchrotron radiaton optical surfaces. Such a comparison is illustrated in Fig. 4.1, in which the LTP profile of the SRI CAT 1-BM focusing mirror is compared to that obtained with a synchrotron x-ray beam from the 1-BM source during the commissioning of the mirror. Although the two methods probe different spatial frequencies, the two profiles show almost identical features. The slight discrepancy towards the right edge (see Fig. 4.1) is believed to be largely due to the mirror mounting in combination with the way the data were processed. Also, note that the LTP profile was taken with a 2-mm lateral resolution at 630.8-nm wavelength, while the x-ray scan was obtained with a lateral resolution of approximately 5 mm at 1.24-nm wavelength (or 10 keV). As one can see from the figure, the mirror is not perfectly flat; the two humps at the edges are due to the manufacturer's polishing techniques.
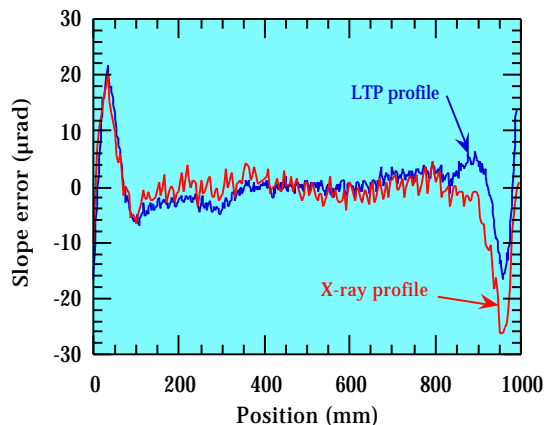

Fig. 4.1 SRI-CAT 1-BM focusing mirror: comparison between the LTP profile (blue curve) and the x-ray profile (red curve) measured during the commissioning of the mirror under the x-ray beam from 1-BM source (see text for more details). Note that the x-ray profile was measured by J. Lang, G. Srajer, and J. Wang of SRI-CAT at the Advanced Photon Source.

An Unusual Case

To date, almost all measured mirrors are within the users' specifications. The exception was one 800-mm-long flat Zerodur mirror, whose surface showed some

discontinuities apparently not seen during the manufacturing process. The imperfections revealed by the LTP scans (see Fig. 4.2) were confirmed by subsequent measurements performed using our WYKO-6000. Several LTP scans taken across the mirror showed that the observed imperfections are not localized ones but are rather spread all across the width of the mirror.
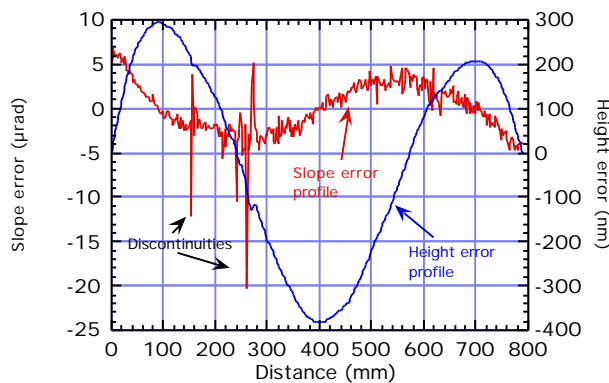

Fig. 4.2 *Discontinuities revealed by the LTP profile of an 800-mm-long Zerodur mirror. The detected imperfections were confirmed by measurements performed using our WYKO-6000 profiler.*

Improvements to the LTP

The LTP was mainly designed for measuring mirrors face up. Recently, we extended its capability to evaluating mirrors and benders in three different deflecting configurations: horizontal, vertical, and side ways. We achieved this by adding a modular optical scanning arm to the LTP optical head. The scanning arm is made of a double pentaprism system mounted using commercially available mechanical components. This provides a means of rapidly and accurately calibrating a mirror-bender assembly before installation in the beamline. Fig. 4.3 shows the example of a Bio-CAT mirror-bender assembly under calibration using the described system. The mirror was mounted face down and was held against gravity by a series of tension springs distributed along the mirror length. The mirror's reflecting face was adjusted to be almost perfectly flat after only a few LTP scans, a task that would have required a considerable effort using online x-ray measurements.
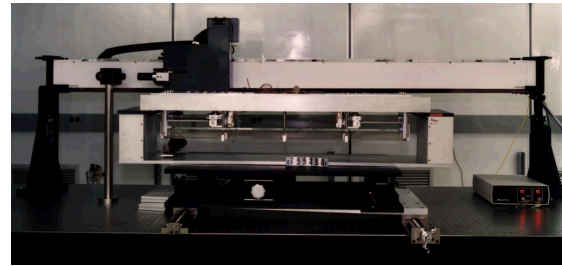

Fig. 4.3 *Photograph of a Bio-CAT mirror-bender assembly under the LTP. A double prism scanning arm was added to the LTP optical head in order to be able to scan the mirror face down (i.e., its final configuration). The mirror is held against gravity by a series of tension springs evenly distributed along the mirror length. The surface of the mirror was adjusted to almost a perfect flat in just a few LTP scans, a task that would have required a considerable effort and time using on-line x-ray testing.*

Other Improvements and Near Future Projects

Other improvements in the metrology laboratory include: a) connection of the individual computers of these instruments to the APS network, which will make the data accessible for analyses and will provide easy access to results of measurement for users for publication purposes, etc.; and

b) development of a metrology laboratory Web page.

Near future projects under consideration include: a) acquiring a mechanical stylus profiler to cover a wider range of applications, b) providing the AFM with a stage to accommodate large optics, c) providing the WYKO-6000 figure interferometer with a high-precision stage for evaluating large mirrors at grazing incidence angles, thus complementing the LTP, and d) upgrading the TOPO instrument.

4.1.2 Deposition Laboratory

Work Progress

Our coating facilities are running smoothly and successfully. We have carried out over 100 regular depositions since April 1997. Over 400 mirrors and experimental samples have been made. All deposition requests from users have been completed promptly. X-ray multilayer mirrors, multistrip mirrors, microfocusing mirrors, and x-ray lithography samples have been fabricated using magnetron sputtering. Using house-invented precision-temperature-controlled evaporators, $Fe^{57}Sn^{119}$ alloy samples have been made by co-evaporation.

Increased productivity has been achieved through the design of universal substrate holders. Multiple samples with arbitrary shapes can be loaded into both the large and the small deposition systems without the need to make individual holders. The coating capability in the small deposition system has been expanded to maximum allowable dimensions of 4" wide, 1.2" high, and 9" in length.

Two 3"-diameter sputter guns have been added in the 1.5-m deposition system. Four different materials can now be coated without breaking the vacuum. RF sputtering for coating insulating materials is also available.

The loading system for the large deposition system has been improved for easy handling of large mirrors. Substrates are loaded inside an air-class 1 clean-hood. Small components and mirrors can be cleaned in the clean-hood before deposition. A UV drying lamp has been installed in the large deposition system to degas the substrates before deposition.

Multilayer Growth and Characterization

Multilayer x-ray mirrors and experimental samples are routinely fabricated. A 100-bilayer W/C multilayer x-ray mirror made for CHESS showed a high reflectivity of 74.1% and a low bandwidth of 1.8%. Figure 4.4 shows x-ray reflectivity data for a W/C multilayer.

Ellipsometer for Thin Film and Multilayer Characterization

A spectroscopic ellipsometer, the M-44 Ellipsometer manufactured by the J. A. Woollam Co., has been added in the deposition lab for both *in situ* and *ex situ* thin film characterization. In ellipsometry, a light beam of known polarization is incident on the sample, and the polarization of the
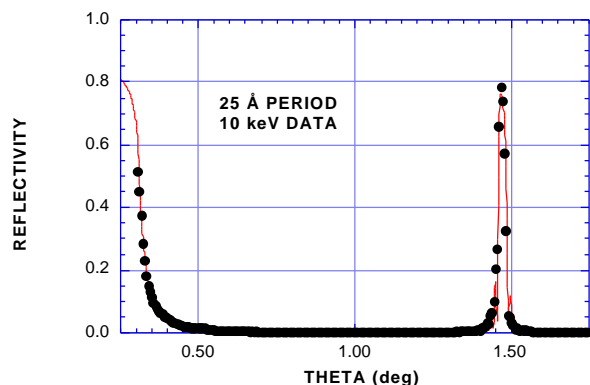
Fig. 4.4 X-ray relectivity for a W/C multilayer grown at the APS.

reflected beam is measured and analyzed. The interaction of the beam with the sample causes changes in the polarization of the light. In general, the reflected light is elliptically polarized. Analyzing the shape of this ellipse (hence the term "ellipsometry") can reveal the physical properties of the sample. Usually, ellipsometry is used for dielectrical/semiconducting materials. For metal thin films less than a few tens of nm thick, however, the light will reach the lower interface and the measured quantity will be sensitive to the thickness. Most of our mirror and multilayer coatings fall within this thickness range.

The accuracy of ellipsometry measurements for thin films depends on knowledge of the exact optical constants of the film, which are often not available. Extensive experimentation with different thin film systems has been carried out to meet this challenge. Sputtered thin films with incremental thicknesses were analyzed using *in situ* ellipsometry with their thickness correlation in mind. We found that the optical constants are thickness dependent for most metal films. Once the optical constants are found for each thickness range, the film thickness

can be more accurately measured using ellipsometry.

Ellipsometry can be used to measure multilayer structures once the optical constants are obtained for each component. Figure 4.5 shows the result for a W/C multilayer. Psi ( ) and delta ( ) are called "ellipsometer parameters." They are related to the ratio of Fresnel reflection coefficients R_p and R_s for p- and s-polarized light as follows: R_p/R_s = tan( )exp(i). These parameters can be fitted with a regression analysis using the film thicknesses as variables. In the present example, the resulting thicknesses agree with that of the x-ray results within 4%. The ellipsometry experiments demonstrate that good quality control can be expected for our thin film and multilayer coatings.
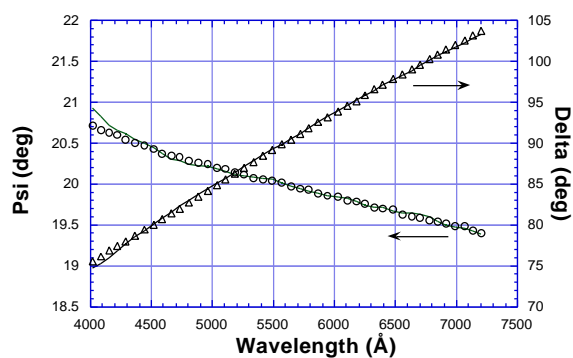

Fig. 4.5 Ellipsometry data and model fit for a W/C multilayer.

4.1.3   Fabrication Laboratory

The fabrication laboratory served the APS user community by preparing and/or improving different elements (predominantly crystals) for x-ray beamlines. In total, over the past year, the lab manufactured 120 new crystal elements, improved or modified 12, and initiated production of 22 others.

Requests completed included such elements as cryo-monochromators, interferometers and diced analyzers. Improvements and/or modifications of crystals already being used on the beamlines consisted of such operations as reshaping, repolishing and re-etching. Forty five percent of orders originated from other than SRI-CAT users, namely from Bio-CAT, BESSRC-CAT, IMM-CAT, PNC-CAT, MU-CAT, MHATT-CAT, UNI-CAT, CARS-CAT and DND-CAT.
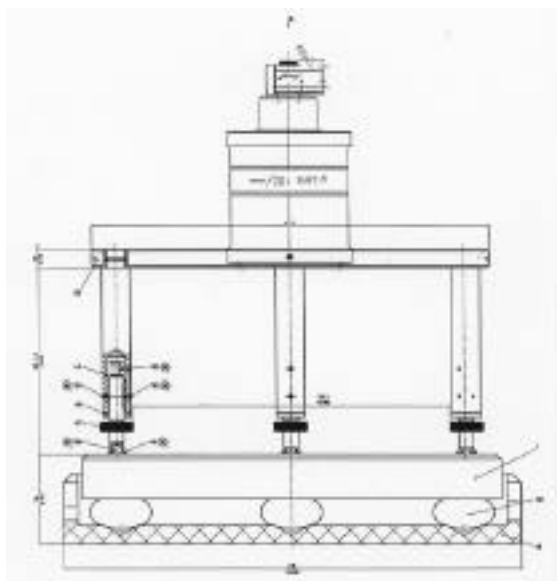

Fig. 4.6   Schematic of the FISBA Optik MicroPhase setup. Shown in the drawing, looking from top to bottom, are a small Twyman-Green-type interferometer, a system of lenses, the base with three legs equipped with regulation screws, a granite base, vibration-isolation pads, and the support box.

The fabrication laboratory is now equipped with its own interferometer. The FISBA Optik MicroPhase setup is a compact modular-type instrument consisting of a small Twyman-Green-type interferometer connected by a fiber guide to a laser (Coherent, Model #200) and mounted on the top of a system of lenses called a beam extender (see Fig. 4.6). The extender is fixed to a base standing on a vibration-isolated granite plate on three screws. The measured object is placed on the granite plate under the beam extender. Operation of the instrument is controlled by a PC. The system utilizes phase-shifting interferometry and allows one to measure the flatness of optical surfaces of a diameter up to 4". The interferometer measuring range is about 10 , and its accuracy is about /10.

4.1.4 X-ray Characterization Laboratory

The x-ray characterization laboratory serves the APS users by giving them the opportunity to orient and test single crystals and to test multi- or single layers deposited on different substrates.

A single-axis diffractometer and a Laue camera were utilized for crystallographic orientation of numerous crystals, predominantly the ones needed in the fabrication laboratory. It is worthwhile to give some examples of the use of other capabilities of the lab. For instance, the double-axis diffractometer placed on a Rigaku x-ray generator was employed to test interferometers that were later investigated with synchrotron radiation, while the left port beam from a Spellman generator was utilized for investigations of archeological samples. However, the main experimental activities in the lab were concentrated at the rotating anode generator.

The Topo Test Unit (TTU) was used for topographic testing of 67 silicon crystals

(monochromators and analyzers already manufactured, and ingots to be used for fabrication), 12 diamond plates, and 10 crystals of other type (germanium, silicon carbide, sapphire). The majority of samples came from XFD staff, but some tests were done for users from BESSRC-CAT, Bio-CAT, MHAT-CAT, MU-CAT and IMM-CAT. Interesting topography results (see Fig. 4.7) were obtained for pin-post monochromators manufactured for Bio-CAT by Boeing North American, Albuquerque Operations. The measurements revealed patterns of strain present in the diffracting

Fig. 4.7 Topograph of the Si (111) pin-post monochromator #1 revealing a characteristic pattern of strain in the region of the heat exchanger. Silicon reflection (333) and 8-keV photons were used in the experiment.

silicon layers that could be attributed to the geometry of the heat exchangers and the bonding technology. The TTU was also used to measure angles between crystallographic and physical surfaces. A series of such measurements was done for Fermi Lab.

The triple-axis diffractometer was used for reflectivity measurements of 26 multi- or single layers deposited on glass or silicon substrates. Most samples were produced in the deposition laboratory. The measurements supplied data needed for deposition of final beamline optics products and/or characterized samples utilized later for synchrotron radiation investigations.

The available equipment in the x-ray lab was enhanced by preparation of some new monochromators and analyzers, e.g., germanium (400) and silicon (620) monochromators for new topographic experiments.

4.1.5 X-ray Mirror Design and Characterization

Post-Monochromator Mirrors

Over the past two years, a large number of x-ray mirrors have been designed and commissioned at the APS. Many of these are positioned downstream of the monochromators and thus received monochromatic beams. Their function is often a combination of focusing, harmonic suppression, and beamline branching. Most of these mirrors are evaluated for surface quality or are coated (single and multilayer) here at the APS. The coatings are characterized using both optical (visible) and x-ray techniques.

For rapid characterization of mirrors and single- and multilayer-coated substrates (e.g., evaluation of coating quality and thickness for establishing deposition rate in the deposition laboratory), a laboratory x-ray system consisting of a Spellman x-ray source and a suitable beam guide has been designed and is being assembled. X-rays are produced by a conventional x-ray tube (Cu or Mo targets) with a maximum power of 2 kW. A horizontal beam from this source is directed, consecutively, through a slit, a monochromator, another slit, a beam scatterer (to determine photon counts by a bicron scintillation detector), and through another slit onto the mirror being analyzed. The mirror is placed on a Bede stage that is designed to fit onto a -2 goniometer, and the two in combination provide the necessary smooth rotation and translation of the sample for detailed mirror surface analyses. The reflected beam from the substrate passes through a slit and an analyzer to a Bede detector, which has over 5 orders-of-magnitude linear dynamic range. The stage, goniometer, and several of the slits are motorized for rapid sample evaluation. Standard APS beamline data acquisition hardware and software are used with a friendly computer interface on a Sun workstation. Design of this system is completed, and hardware are ready and in final stage of assembly. Additionally, a compatible but modular setup at the APS sector 2 bending magnet beamline is planned so that samples evaluated in the lab can also be easily tested on a beamline.

Mirrors as First Optical Elements

In addition to the post-monochromator mirrors, an increasing number of APS beam-lines (at least 6) use or plan to use a mirror as the first optical element. This approach to beamline design has been motivated, at least in part, by the success in the design of simple high-heat-load mirrors at the APS and by their reliability and ease of operation established over the past two years. As an example, the contact-cooled high-heat-load mirror at the sector 2 undulator beamline of the APS has been operating for two years without any mirror-related downtime. The preliminary thermal and structural performance of this mirror at commissioning and during subsequent observations indicates a tangential rms slope error of about 2-4 μrad (Khounsary et al., 1998); a precise measurement of the mirror has been planned for this summer (1998).

Plans have also been made for precise re-evaluation of this mirror using 'pink' beam radiation this summer. For this, we have designed a cooled composite slit array consisting of a thin copper plate with thirty holes, each 60 μm in diameter and located at 300-μm center-to-center intervals, masking another slit array of thirty 30-μm holes configured in a thin tantalum plate. These two plates are aligned, with the one having larger holes acting as a thermal shield for the second plate. Pink undulator beam reflected from the mirror passes through the slit array and is recorded on a charge-coupled device (CCD). Transient and steady-state tangential slope errors in the mirror under various heat load conditions are mapped from the shifts in the slit images on the CCD camera.

Another attribute of the mirror-first beamline design is the ability to use a water-cooled monochromator downstream of the mirror. A simple contact-cooled monochromator—dubbed U-monochromator for its U-shaped cross section—was designed, installed, and evaluated. Both early evaluations (Lee et al., 1997) and recent experience indicate that this contact-

cooled monochromator is capable of comfortably handling post-mirror undulator beam.

Mirror Characterization Using an *in situ* LTP

Another set of measurements aimed at evaluating mirror performance under high-heat-load x-ray beam was made using an *in situ* long trace profiler developed at the APS sector 2-ID beamline in collaboration with Brookhaven National Laboratory. In this setup, a laser beam scans the length of a contact-cooled high-heat-load 200-mm-long mirror to determine its transient and steady-state slope errors. Preliminary results (Takacs and Randall, 1998) indicate a thermally induced slope error of about 7 µrad at steady-state conditions and a thermal time constant of about 10 minutes. These are in excellent agreement with design predications made earlier (Khounsary and Yun, 1996).

X-ray Mirror Design for Higher Beam Powers

As new generations of vacuum chambers make smaller undulator gap openings possible and as enhancement in storage ring capabilities make ring operation at higher beam currents possible, the ramifications of using mirrors as first optical elements with substantially higher power x-ray beams need to be examined. A program aimed at developing mirrors for higher heat loads has led to a design that is expected to meet the requirements.

With closer undulator gap and/or higher storage beam current, the heat load on mirrors used as the first optical element will be substantially increased. At a gap opening of 11.5 mm, a typical 1.2-m-long mirror located at about 30 m from the source at a 0.15° angle with respect to the x-ray beam (reflecting photons up to 35 keV with a Pt coating) receives about 1.2 kW of power and a peak heat load of about 0.4 W/mm^2. The maximum temperature and rms slope errors are 45°C and 2 µrad, respectively. At a closer 10.5-mm gap and a hypothetical 300-mA storage ring current, the incident heat load on the same mirror will be 5 kW with a peak heat flux of 1.5 W/mm^2. The increased heat load lead to higher temperature, higher slope errors, and higher stress in the mirror. While moderate heat load increases (up to about 30%) on the present mirrors can be tolerated at the cost of about 50% increase in slope error, more significant increases can lead to unacceptable temperature, slope errors, and stresses.

We have embarked on designing another simple contact-cooled mirror aimed at handling, with acceptable performance, the above hypothetical heat load. The key features of this mirror design are (1) introduction of a pair of notches in the mirror substrate (see Fig. 4.8) for a more effective thermal moment balance in the substrate, (2) replacement of the indium foil used as interstitial material (between the copper cooling and silicon mirror) with In/Ga eutectic for a more efficient heat transfer, and (3) an increase in the cooling block width to reduce substrate temperature. Preliminary analyses indicate that incorporation of these three features would lead to a mirror with under 5-µrad slope error with a maximum temperature of about 80°C for the above hypothetical power load. Stress levels in the mirror are high, and a prototype should be made and tested under simulated heat-load conditions.
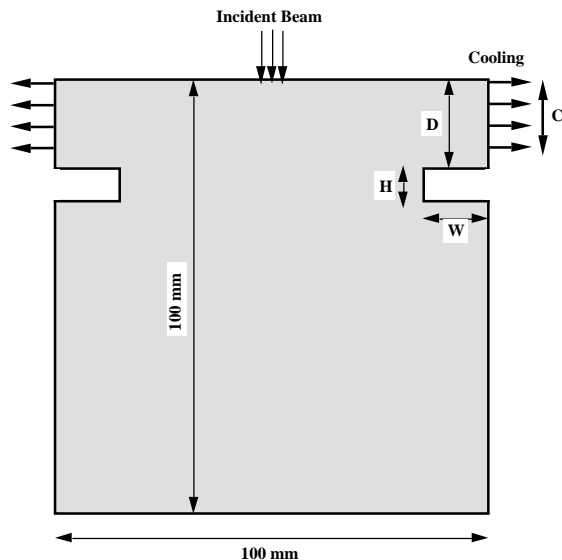
Fig. 4.8 The cross section of a 1.2-m-long mirror showing a pair of notches that help establish a thermal profile in the substrate, which restores thermal moment balance keeping the mirror tangentially (into the paper) close to flat. With an incident undulator A beam power of over 5 kW, a slope error under 5 μrad is expected.

Beryllium Window Evaluation and Characterization

Another issue related to mirrors—whether high heat load or not—is the surface quality and its impact on x-ray beams. Most x-ray mirrors installed at the APS have very fine figure and finish, typically in the range of 2-5 microradians and 2-4 Å, respectively. There is some questions as to whether speckles seen in some x-ray images are related to the mirror surface quality or the beryllium (Be) windows used on these beamlines. To that end, the APS has initiated a collaborative effort with the Be window manufacturer, Brush Wellman, to determine whether the observed speckles resulting in beam quality degradation are due to the Be windows or to the mirror surface, and if, as believed, the Be window is the culprit, the APS will develop guidelines for window surface in order to reduce or eliminate the observed beam quality degradation.

To determine the effect of Be windows on beam quality, in collaboration with Brush Wellman, a pair of Be windows have been designed for installation on an APS beamline. A number of Be foils of varying surface roughness are made and are being evaluated at the APS, using both optical (visible) and x-ray techniques. For the first time, very thin (250-μm-thick) Be foils have been polished to very fine finish (as low as 100 Å rms) on both sides and from various Be grades (cold-rolled and bulk). After these are characterized, the smooth foils are brazed to the cooled window frame to provide a pair of smooth, cooled Be windows for installation on an APS beamline. Residual beam degradation, if any, should then be due to x-ray mirrors. This work is in progress.

Phosphor Coating for CCD Detector

One aspect of the CCD detector development at the APS involves phosphor coating of the fiber optic substrates for high efficiency and resolution. A new in-house coating technique is being developed to replace the existing but often complex coating methods that produce poor quality coatings with significant residual chemical waste. The method consists of controlled spin-coating of the phosphor, prepared in a suitable solution, onto substrates producing very smooth coatings. Another goal of this work is to develop and evaluate fiber optic substrates with a layer of phosphor and an additional antireflection film directly

deposited on them to make simple, integrated substrates for use in x-ray detectors.

4.2 Beamline Controls and Data Acquisition

The XFD beamline-controls effort has two complementary missions of approximately equal priority: (1) to develop general-purpose control and data-acquisition software that all APS CATs can use and provide technical support to CAT developers; (2) to implement software and computer-related infrastructure (network, file server, workstations, printers, etc.) for the SRI-CAT beamlines and laboratories. This arrangement implies that SRI-CAT users test software for the rest of the facility and provide much of the feedback directing its development. Our contact with other APS users is generally indirect, through their developers.

Nearly all APS beamlines run XFD-developed software, though the implementations vary from CAT to CAT. Some CATs run virtually the same software as does SRI-CAT, from user interface through low-level drivers; others run our low-level and middle-level software in their VME crates and supplement or replace our user-interface layer with their own custom software. The APS Beamline Controls Collaboration, which includes developers representing all APS CATs, chose EPICS as the basis for beamline software development in part because it allows for this kind of flexibility of implementation.

EPICS does not guarantee this flexibility, however; nor does the mere implementation of support for a device (e.g., an optical table) or a technique (e.g., on-the-fly scanning) in EPICS software guarantee that the support can be used facility-wide. Aside from the quality of a software module, the layer in which it is implemented determines whether it can be run by higher-level software and whether it can run lower-level software. Software that can do both provides the greatest flexibility, and consequently much of our focus is on this kind of software.

Most of XFD's beamline-software development effort is in server-side software—the low-level and middle-level software that runs in VME crates—as opposed to client-side software that runs mostly on workstations. Roughly half of our development is of driver software, which interacts directly with hardware and clearly must run on the server side. But much of the rest could be done either in server or in client software, and we choose server-side development whenever possible—sometimes even when client-side would be a more natural choice—because anything implemented in server software can be used by all CATs, regardless of their choices of client software, workstation type, and operating system.

The past year's development effort has focused on five general areas: improvements in scan and data-storage software; support for message-based devices; support for remote beamline operation; support for new devices; and exploratory studies of software, hardware, and techniques that may one day become useful in beamline control.

4.2.1 Improvements in Scan Software

The EPICS scan software described in last year's report worked around a fundamentally limited completion detector—the mechanism for determining when positioners or detectors have completed their movements or acquisition. The old completion detector could be fooled by network latency into thinking that a set of positioners was done if the "busy" and "done" messages from one positioner were received before the "busy" message from another was received. The completion detector also required developers to maintain a list of all slow devices eligible for scans. This list had to be modifiable at run time, and the implementation of that requirement limited scan speeds to a few tens of data points per second. Finally, the completion detector was confusing to new users and a frequent source of trouble.

The new scan software takes advantage of recent improvements in EPICS that allow it to track the flow of execution through a complex assembly of software modules linked together at run time, and to report completion of the entire assembly to the module that initiated the operation. We modified the scan software to use this new capability as a completion detector. Most of our custom records, databases, and sequence programs also required modification, to follow the new rules that allow this completion detector to function properly.

The resulting system allows users to scan any correctly implemented device without identifying it in advance to the scan software, is unaffected by normal network latency, and is nearly an order of magnitude faster than the old system. Scans can now acquire several hundred data points per second, significantly extending the range

beyond which custom hardware (e.g., waveform generators and multichannel scalers) is required. One type of run-time coordination supported by the old completion detector is no longer supported directly, although users sophisticated enough to require that type of coordination can program the new scan software to run the old completion detector as a pseudo positioner.

4.2.2 Improvements in Data-Storage and Display Software

The data-storage and display software described in last year's report consisted of a single client program running on a workstation. That arrangement was expedient and got us through a few difficult years, but it put storage and display priorities in conflict, and resulted in a complex event loop that made the software difficult to maintain end extend. Also, the dual-use program allowed users to delete online data, and one user did this unintentionally.

Now, data storage is handled by a client running in the VME crate that writes directly to the file server. Normally priviledged users can no longer delete raw data, and data storage continues through workstation reboots, license-manager restarts, etc.

Display software for online data is now handled by a separate program with no responsibilities other than display. The program is still somewhat complicated because it must monitor real-time data using EPICS calls and read recently stored data from data files. (For scans of two or more

dimensions, both real-time and stored data must be displayed.)

For long-term data storage, and for exporting data to users' home facilities, the plan is still to use the Hierarchical Data Format (HDF) based file format agreed on by the APS Beamline Controls Collaboration and supported by third party browsers and some data-analysis packages. This format, now called NeXus, has evolved significantly in recent years, and the performance of HDF has improved as well, though we still cannot write NeXus files fast enough to keep up with real-time data acquisition.

4.2.3 Support for Message-Based Devices

Visiting APS users occasionally bring special-purpose serial or GPIB devices with them and need to integrate support for these devices into the control system. CARS-CAT developed generic modules to send and receive strings to/from serial and GPIB ports, but users still have to format and parse the strings. Until recently, that task required custom client software, and the resulting device support could not be used by server-side software. We filled part of the need with boot-time configurable modules that server software could call, but the result was unsatisfactory, arcane, and difficult to maintain.

This year we bridged the gap by adding string support to EPICS run-time programmable calculation software (with which many users already are familiar). Now run-time programmable support for message-based devices behaves just like native EPICS device-support software, is

useable both by client-side and by server-side software, and can easily be programmed by users. This means we can fully integrate selected functions of most serial or GPIB devices into the control system in a few minutes.

4.2.4 Support for Remote Beamline Operation

EPICS has always provided for shared local/remote beamline control. The capability has thus far been used mostly by developers for technical support and by a small number of users to do simple things like checking the progress of very long-running scans from home.

This year we found a user for serious remote beamline operation. We wrote software to manipulate a remotely controllable video camera using an unmodified Web browser, modified some public-domain software to send selected video streams (also to an unmodified browser), installed standard EPICS client software on a workstation at the University of Florida, and demonstrated running a beamline from there to an audience of developers, users, and program directors.

4.2.5 Other Highlights

Over the past year, we responded to roughly 2300 tech-support requests. This number is significantly lower than last year's, and the requests are qualitatively much different. We received relatively few requests for hardware information, since most of that information is now on our Web pages. Most of the CAT developers are well up the EPICS learning curve by now, and our Web-

based software documentation is also much improved. The requests we do get generally are more complex than in previous years and, on average, take much longer to handle.

We performed system and network administration for six beamlines and related labs. The control systems supported by our group now comprise 27 VME crates, approximately 60 computers, and 12 printers.

We hosted the second international NOBUGS (New Opportunities for Better User Group Software) workshop for software developers from synchrotron-radiation and neutron-scattering facilities. Of 106 participants, 49 were from Argonne, including 31 from the APS.

We have largely taken over EPICS builds for the APS project and distribution of most EPICS software for the EPICS collaboration. We also have begun contributing to the maintenance of Hideos software and VxWorks board-support software on both of which most APS beamline-control systems depend.

In addition, we have:

- Developed support for two new optical-table geometries and now allow for fewer than six degrees of freedom

- Delivered 110 motor-signal interface boards to CATs, bringing the total to 300

- Converted all SRI-CAT workstations from the SunOS operating system to Solaris

- Solved the input-termination problem in the StepPack motor-driver interface board and fabricated sufficient patch kits for all APS beamlines

- Developed hardware and software support for servo motors, piezo-drivers, and the Keithley 2000 scanning digital multimeter

4.3   References

Khounsary, A. M., W. Yun, B. Lai, I. McNulty, Z. Cai (1998) "Performance of side-cooled high-heat load mirrors," paper presented at the SPIE Conference on Advances in Mirror Technology for X-ray, Synchrotron, and Laser Applications Conference, San Diego, July 20, 1998.

Khounsary, A. M. and W. Yun (1996) Rev. Sci. Instrum. **67** (9) CD ROM.

Lee, W-K., P.B. Fernandez, A. Khounsary, W. Yun, and E. Trakhtenberg (1997) SPIE Proc. Vol. **3151**, 208-215.

Takacs, P. and K. Randall (1998) "Mirror distortion measurements with an in situ LTP," paper presented at the SPIE Conference on Advances in Mirror Technology for X-ray, Synchrotron, and Laser Applications Conference, San Diego, July 20, 1998.